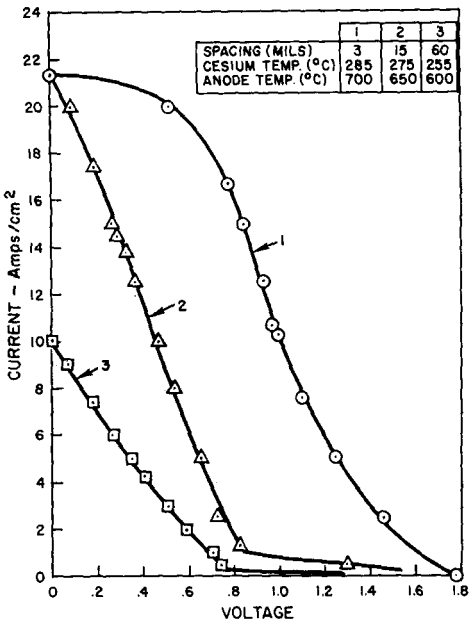

FIG. 2. The effects of electrode spacing on volt-ampere characteristics at a cathode temperature of 1650°C.

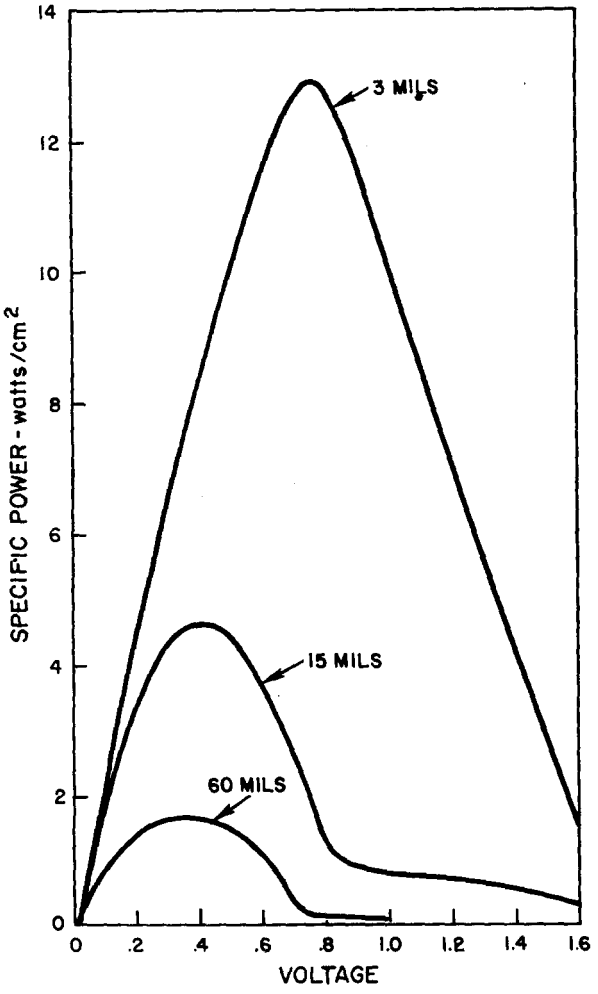

FIG. 3. The effects of electrode spacing on power characteristics at a cathode temperature of 1650°C.

the required variations in each of these parameters was small. Figures 2 and 3 indicate the changes in the volt-ampere and power characteristics as a function of spacing. The characteristic at 0.003 in. departs from the resistive characteristics seen at the larger spacings, and its form begins to resemble the characteristic of an emission limited converter. The fact that maximum power occurs at an emf approaching the difference in work functions (about 1.1 v) is a further indication of the approach to the emission limit.

At 1650°C and 17 amp/cm² it is interesting to note that the ratio of radiative to electronic cooling is less than 8%. This converter was built as a research tool and was not meant to provide high efficiency. Nevertheless, the ratio of power output to heater power input approached 9% at the high specific powers. In a more desirable geometry in which all parasitic losses have been minimized, this would correspond to over-all efficiencies near 25%.

The author gratefully acknowledges the assistance of Dr. N. S. Rasor and J. M. Nuding, H. G. Barrus, R. C. Dahleen, and C. C. Weeks, without whose help this work would not have been possible.

Influence of Arsenic Pressure on the Doping of Gallium Arsenide with Germanium

J. O. McCALDIN AND ROY HARADA
Hughes Semiconductors, Newport Beach, California
(Received May 23, 1960)

THE doping of III–V compounds with elements from the IVth column of the periodic table has been studied under standard conditions of preparation by several investigators.[1–6] In most cases, the IV element was found to act as an n-type dopant of low doping efficiency, a result that is usually interpreted to mean that more of the impurity atoms are located on the III element sublattice than on the V element sublattice. Causes for the unequal distribution of impurity atoms between the two sublattices have been sought in the sizes of the atoms and in their binding energies.[4] An additional influence on the impurity atom distribution, namely, the vapor pressure of the V element, is considered in this note. A simple estimate will be given of the magnitude expected for the pressure effect, followed by some qualitative results for Ge-doped GaAs.

Suppose the III–V compound is composed of a relatively nonvolatile element located at A sites of the lattice and a volatile element located at B sites. Qualitatively, one might expect that higher pressures P_B of the volatile element would reduce the concentration V_B of vacancies at the B sites; consequently, a IV element like germanium would tend to move to an A site, where it acts as a donor. Similarly, a reduced pressure P_B would shift the Ge atoms to B sites, where they behave as acceptors. The transfer of a Ge atom from an A site to a B site may occur with the participation of the appropriate vacancies V,

$$\mathrm{Ge}_A + V_B \rightleftarrows \mathrm{Ge}_B + V_A. \tag{1}$$

The actual reaction may be more complicated than (1). The reacting species, for example, are probably ionized to a large extent. Let us assume that, at the high temperatures at which equilibrium is reached, the intrinsic concentration n_0 of conduction electrons is considerably larger than the concentrations of the reacting species, so that ionization reactions do not affect the equilibrium appreciably.[7] Writing a mass action relation for the equilibrium between vacancies and Ge atoms,

$$N_{\mathrm{Ge}A}/N_{\mathrm{Ge}B} = K_2 N_{VA}/N_{VB}. \tag{2}$$

The vacancy concentration N_{VB} depends[8] upon the pressure P_B

$$N_{VB} P_B = K_3 \tag{3}$$

assuming a monatomic gas. A similar relation can be written for the A (i.e., column III) species, and the two pressures P_B and P_A

can also be related[8]

$$A_{\text{gas}}+B_{\text{gas}} \rightleftarrows AB_{\text{solid}} \cdots P_A P_B = K_4. \quad (4)$$

Assuming equilibrium, we may eliminate P_A and write Eq. (2) as

$$\frac{N_{\text{GeA}}}{N_{\text{GeB}}}\left(\frac{P_B}{P_{BO}}\right)^{2r}, \quad (5)$$

where the exponent r is introduced to allow for a gas phase which is not monatomic (for arsenic vapor, $r=\frac{1}{4}$), and P_{BO} is the vapor pressure for which the impurity atoms are distributed equally between A and B sites. The last equation indicates that a tenfold increase or decrease of the pressure P_B from the reference pressure P_{BO} should make the IV impurity a rather effective donor or acceptor dopant, respectively.

The equilibrium relationships just described have been investigated qualitatively by diffusion treatments of Ge-doped GaAs. A GaAs ingot was grown from a melt doped with 2% Ge in a horizontal Bridgman furnace. The melt was contained in a carbonized quartz boat enclosed in an evacuated sealed quartz tube and was frozen directionally at a rate of about 1 in./hr. The arsenic vapor pressure was maintained at 0.9 atm.[9] The resulting ingot was p type at most places; it was polycrystalline with crystallites about 2 mm in size in some regions.

Slices about 0.075 cm thick were taken from the nose of the ingot. Some of the slices were treated 70 hr at 900°C at 5-mm arsenic pressure. These slices, which contained a few deep pits, were everywhere p type at the surface. Other slices were treated 70 hr at 1100°C at 5 atm arsenic pressure. These slices became everywhere n type at the surface. Metallographic sectioning followed by etching (1 pt. HF, 5 pts. HNO_3) revealed a p-n junction underlying the surface at a depth ranging from 30 μ to 70 μ at most places and penetrating considerably deeper at grain boundaries. The behavior at grain boundaries is probably related to the kinetics of vacancy formation. Also the junction within individual grains was scallopped, probably for similar reasons. Capacity vs reverse bias measurements made on some of these junctions indicate linear grading for the doping.

The experimental results agree qualitatively with relation (5); however, only the specimen surface, and perhaps some grain boundaries, could have been close to equilibrium under the experimental conditions. We are now engaged in preparing homogeneous specimens for quantitative measurements.

[1] C. Kolm, S. A. Kulin, and B. L. Averbach, Phys. Rev. **108**, 965 (1957).
[2] D. Jenny and R. Braunstein, J. Appl. Phys. **29**, 596 (1958).
[3] E. Schillman, Z. Naturforsch. **11a**, 463 (1956).
[4] O. G. Folberth and E. Schillman, Z. Naturforsch. **12a**, 943 (1957).
[5] J. T. Edmond, Proc. Phys. Soc. **73**, 622 (1959).
[6] J. M. Whelan, J. D. Struthers, and J. A. Ditzenberger, Bull. Am. Phys. Soc. **5**, 152 (1960).
[7] The effects of ionization on amphoteric impurities like the Ge atoms of the present case have been treated by R. L. Longini and R. F. Greene, Phys. Rev. **102**, 992 (1956).
[8] J. J. Lander and D. G. Thomas, in *Semiconductors*, edited by N. B. Hannay (Reinhold Publishing Corporation, New York, 1959), Chap. 2 and 7.
[9] J. van den Boomgaard and K. Schol, Philips Research Rept. **12**, 127 (1957).

Noise Propagation in Drifting Multivelocity Electron Beams

J. A. MORRISON
Bell Telephone Laboratories, Inc., Murray Hill, New Jersey
(Received June 21, 1960)

BERGHAMMER and Bloom[1] have recently published an approximate analysis (hereafter referred to as [1]), based on a macroscopic model, describing the behavior of the noise parameters in a multivelocity beam in which the velocity spread is assumed to be sufficiently small that the third-order moment (about the mean) of the distribution function may be neglected. They derived differential equations for the variation of the noise parameters with distance along the beam and in addition obtained two conservation laws. The differential equations were solved for the particular case of a drifting beam, with uncorrelated full shot noise being assumed at the input plane. The case of a half-Maxwellian dc density distribution was considered in detail. It is the purpose of this letter to point out that the formulas they give for the noise parameters S and Π do not agree with the results of numerical computations based on the distribution function method of Siegman *et al.*,[2,3] which were carried out in the above case for a moderately high drift voltage, and were reported by J. R. Pierce.[4] These calculations are based on the same physical assumptions as [1], with uncorrelated full shot noise in each velocity class, but do not involve the approximations made in [1] because of the assumption of small velocity spread.

The computations were carried out in a manner similar to that adopted by Siegman, Watkins, and Hsieh and were programmed for the IBM 704 by D. E. Eastwood. The frequency ω was taken to be 3 kMc and the cathode temperature T_c to be 1000°K. The accompanying figures depict, for two different values of the dc beam current I_0, the variation of the normalized noise parameters with normalized distance along the beam, which is taken to be drifting at 1 v. In terms of the quantities in [1] the normalized noise parameters in Figs. 1(a) and (b) are

$$\varphi=\Phi/\Phi(0); \quad \psi=\Psi/\Psi(0); \quad \chi=\Lambda/S(0). \quad (1)$$

In Figs. 2(a) and (b) the normalizing factor is $S(0)$. The normal-

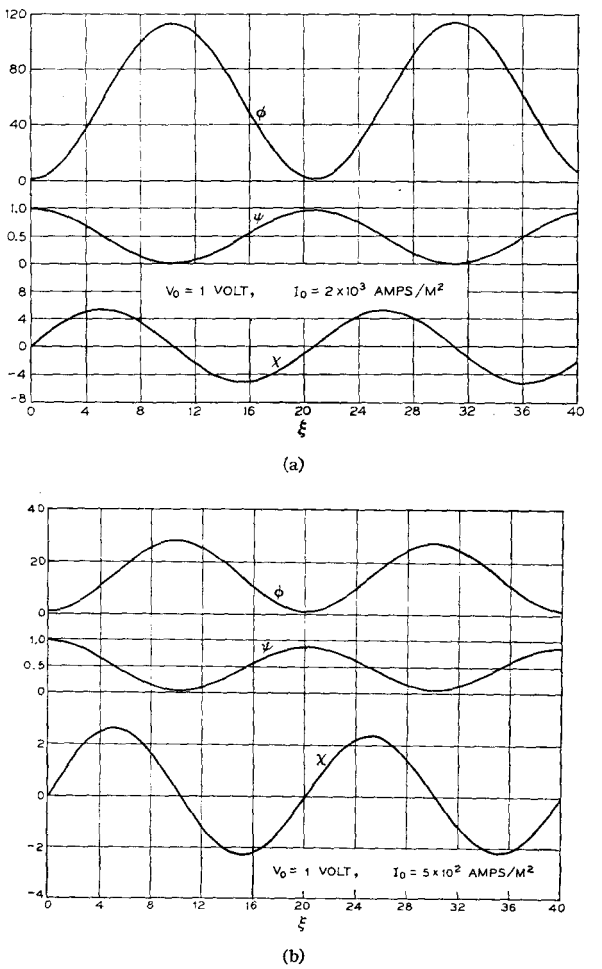

FIG. 1. Variation of the self-correlations, and of the imaginary part of the cross-correlation, of the current and voltage fluctuations with distance along the drifting beam. (a) dc beam current of 2×10^3 amp/m². (b) dc beam current of 5×10^2 amp/m².